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RESEARCH MEMORANDUM

CARBON DEPOSITION OF 19 FUELS IN AN ANNULAR TURBOJET COMBUSTOR

By Jerrold D. Wear and Edmund R. Jonash

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NATIONAL ADVISORY COMMITTEE
FOR AERONAUTICS

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RESEARCH MEMORANDUM

CARBON DEPOSITION OF 19 FUELS IN AN ANNULAR TURBOJET COMBUSTOR

By Jerrold D. Wear and Edmund R. Jonash

SUMMARY

The effects of fuel properties and change in simulated engine operating conditions on carbon deposition were evaluated in an annular turbojet combustor with a diameter of $10\frac{3}{8}$ inches. The fuel properties examined were specific gravity, volumetric average boiling temperature, hydrocarbon type, and hydrogen-carbon weight ratio. The simulated engine operating conditions ranged from sea level and 50-percent rated engine speed to an altitude of 40,000 feet and rated engine speed. The fuels included hydrocarbons of the paraffinic, olefinic, and aromatic types as well as fuel mixtures.

In general, carbon deposition in the annular combustor increased with increase in boiling temperature of fuels of the same hydrocarbon type. Aromatic fuels deposited more carbon than other types of fuel of the same boiling temperature. An empirical correlation of the carbon deposition, the boiling temperature, and the hydrogen-carbon weight ratio of the fuel was obtained.

INTRODUCTION

Carbon deposition in the combustion chamber of a jet-propulsion engine can affect the operational performance, particularly the blow-out characteristics, of the engine. The carbon formations may interfere with the atomization of the fuel from the nozzle and may alter the air-flow pattern through the combustor.

Previous investigations to determine the effects of fuel properties on carbon deposition have been conducted in several types of burner. Results reported in reference 1 indicate that the quantity of carbon deposited in a full-scale jet-propulsion engine apparently is a function of the aromatic content of a fuel; however, no definite correlation between carbon deposition and fuel properties was found.

Because the fuels available for the investigation of reference 1 were complex hydrocarbon mixtures, the effect of change in one fuel property at a time could not be determined.

A laboratory burner capable of controlling the fuel-air ratio and prevaporizing the fuel showed an increase in photoelectrically indicated smoke production with increasing aromaticity of the fuel (reference 2). The clean burner-operation limits of a type of rotary fuel-oil burner for home use were found to correlate with the A.P.I. gravity and the boiling point of fuel oils (reference 3). In England in 1930, the maximum height of smoke-free flames in a lamp was used to demonstrate that the tendency of fuels to smoke varied with aromatic content, naphthene content, and aniline point (reference 4).

An investigation made at the NACA Lewis laboratory to determine the effects of fuel properties and, to a limited extent, the change in simulated engine operating conditions on carbon deposition in a $10\frac{3}{8}$-inch-diameter annular combustor is reported herein. A total of 19 fuels were investigated, including two paraffinic fuels, two olefinic fuels, eight aromatic fuels, and seven fuel mixtures. The effects of varying engine operating conditions were examined for only three of the fuels. The fuel properties examined were specific gravity, volumetric average boiling temperature, hydrocarbon type, and hydrogen-carbon weight ratio. Volumetric average boiling temperature was used instead of 50-percent evaporated temperature because of the wide boiling range of some of the fuels.

APPARATUS AND FUELS

A description of the $10\frac{3}{8}$-inch-diameter annular combustor, which was taken from a commercial turbojet engine, and auxiliary equipment, instrumentation, and location of the instrumentation is described in detail in reference 5.

The fuels used in this investigation included representative hydrocarbons of paraffinic, olefinic, and aromatic types as well as fuel mixtures. A fuel was considered to be a mixture if it contained less than 95 percent of a particular class of hydrocarbon compound. The physical properties and chemical composition of the fuels are listed in table I. Chemical compositions of the fuels were determined by procedures given in references 6 to 9. The net heats of combustion of two of the aromatic fuels were obtained from reference 10.

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PROCEDURE

Carbon-deposition investigations were made with the 19 fuels at one simulated engine operating condition and with three of the fuels at five additional simulated engine operating conditions. The values of the combustor-inlet and combustor-outlet conditions used for the different simulated engine operating conditions were obtained from the manufacturer's estimates of the performance of the turbojet engine from which the combustor was taken.

The simulated engine operating conditions are listed in the following table:

Simulated engine operating condition	Simulated altitude (ft)	Simulated engine speed (percent rated)	Inlet-air total pressure (in. Hg abs.)	Inlet-air total temperature (°F)	Fuel flow (lb/hr)	Over-all fuel-air ratio	Running time (hr)	Turbine-inlet total temperature (°F)
1	40×10^3	100	19.0	132	155.5	0.0282	$1\frac{1}{4}$	1315
2	20	50	18.9	43	116.5	.0224	$1\frac{1}{4}$	1045
3	30	100	30.8	153	172.0	.0202	$1\frac{1}{4}$	1320
4	0	50	40.0	100	157.5	.0175	$1\frac{1}{4}$	1280
5	0	50	40.0	100	157.5	.0175	2	1280
6	20	100	44.0	196	223.0	.0181	$1\frac{1}{4}$	1360

Fuel flow for any one simulated engine operating condition was determined by adjusting the inlet-air conditions to the desired values and varying the flow of AN-F-32 fuel until the required turbine temperature was obtained. This value of fuel flow was used with the other fuels at the desired simulated engine operating condition.

The weight of carbon was obtained by the difference in weight of the combustor basket before and after each run. The combustor basket was clean at the beginning of each run. A diagrammatic cross section of a typical heavy carbon formation at the fuel nozzle in the annular combustion zone is shown in figure 1.

The combustion efficiency of the fuels at the different engine operating conditions were calculated as described in reference 5.

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RESULTS AND DISCUSSION

Limited exploratory investigations were conducted with three fuels in the annular combustor with a diameter of $10\frac{3}{8}$ inches to determine to some extent the effect of running time and simulated engine operating conditions on carbon deposition. The fuels included two aromatics, benzene and aromatic solvent, with approximately 150° F difference in boiling temperature and one fuel mixture, AN-F-32.

The effect of running time, other conditions constant, on the carbon deposition of the three fuels is presented in figure 2. From a running time of $1\frac{1}{4}$ to 2 hours the amount of carbon deposited by aromatic solvent and benzene increased by only about 4 and 17 percent, respectively, whereas the amount deposited by AN-F-32 fuel increased approximately 78 percent. The large reduction in the rate of carbon formation by aromatic solvent and benzene indicates that the rate of carbon removal by burning and eroding is approaching the rate of carbon deposition after about 2 hours for these two fuels. The quantity of carbon obtained with AN-F-32 in 2 hours was probably too small to be affected substantially by burning and eroding. As shown in figure 2, basing the carbon deposition on a per unit-weight-of-fuel basis would not be justified for aromatic solvent or benzene.

Investigations of the three fuels were made at several simulated engine operating conditions to determine if change in engine operating condition would change the order of carbon deposition among the fuels. The data shown in figure 3 indicate that for the three fuels investigated the order of carbon deposition among the fuels remained the same. A change in engine operating condition that increased or decreased the carbon deposition of one fuel also increased or decreased the carbon deposition of the other two fuels. The apparent exception in the case of AN-F-32 from conditions 3 to 4 is probably within experimental error. The combustion efficiencies of the fuels at the different engine operating conditions are included in figure 3. The lowest combustion efficiency of each fuel was observed at condition 2. Conditions 3, 4, 5, and 6 represented very stable high efficiency operation, resulting in combustion efficiencies substantially greater than either condition 1 or 2.

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Engine operating conditions 1, 3, and 6 (fig. 3) show the effect of change in altitude at constant engine speed on carbon deposition for the three fuels. The inlet-air total pressure, inlet-air total temperature, and fuel-air ratio varied with altitude. Carbon deposition of all three fuels decreased with increase in altitude; this decrease occurred with a decrease in fuel flow and an increase in fuel-air ratio.

The effect of change in engine speed from 50 to 100 percent of rated engine speed on carbon deposition at a constant altitude of 20,000 feet for three fuels is shown by engine conditions 2 and 6 (fig. 3). Carbon deposition increased with increase in engine speed. This increase occurred with an increase in fuel flow and, in this case, a decrease in fuel-air ratio.

The data presented in figure 3 indicate that one engine operating condition would be sufficient for relative carbon-deposition investigations of the various fuels. Although the relative amounts of carbon varied among fuels at different conditions, the trends remained the same. Engine condition 5 was used to obtain the carbon-deposition data of the various fuels.

The values of carbon deposition and combustion efficiency of the various fuels obtained in the $10\frac{3}{8}$-inch-diameter annular combustor at engine operating condition 5 are presented in table II. Investigations of several fuels were repeated to determine the reproducibility of the data. The average carbon deposition of the two or more runs for each of the several fuels is also listed in table II.

The effect of fuel blending on carbon deposition is presented in figure 4. The combinations of fuels investigated were paraffin-mixed fuels, paraffin-aromatic, aromatic-mixed fuels, and aromatic-aromatic. The blends of paraffin-mixed fuels, paraffin-aromatic, and aromatic-mixed fuels gave values of carbon deposition that were between the amounts obtained with the two fuels used to make the blends. The two aromatic-aromatic blends, however, gave as much or more carbon than the fuels that were used to make the blends.

The average carbon deposition of the various fuels is plotted against volumetric average boiling temperature in figure 5. The volumetric average boiling temperature is defined as the arithmetical average of the 10-, 30-, 50-, 70-, and 90-percent-evaporated temperatures of the A.S.T.M. distillation methods D 86-45 and D 850-47. This average was used instead of the 50-percent evaporated temperature because of the wide boiling range of some of the fuels. The aromatic contents of the fuels are given in figure 5 beside the data points, and curves are faired through approximately equal values of aromatic content. The carbon deposition of the aromatic fuels (98-percent aromatics or greater) shows an increase with increase in volumetric average boiling temperature. Considerable scatter exists, however, from a faired curve. When approximately constant values of boiling temperature, 170° to 182° F and 360° to 380° F are used, carbon deposition increases with increase in aromatic content. The aromatic fuels gave more carbon than the other types of fuel of the same boiling temperature. 1054

The data of figure 5 are replotted in figure 6 on the same coordinates with the specific gravities of the fuels listed beside the data points instead of the aromatic content. Curves are faired through approximately equal values of specific gravity. In general, carbon deposition increased with increase in specific gravity at approximately constant boiling temperature in the range from 170° to 182° F and 360° to 380° F. A considerable number of data points, however, are not consistent with the faired curves. Carbon deposition increased with an increase in boiling temperature of the paraffinic fuels designated by specific gravities of 0.725 and 0.775 and mixed fuels designated by specific gravities such as 0.728 and 0.814.

The data of figures 5 and 6 are replotted in figure 7 on the same coordinates, with the hydrogen-carbon weight ratio of the fuels listed beside the data points. Curves are faired through approximately equal values of hydrogen-carbon weight ratio. There appears to be a general trend of carbon deposition with volumetric average boiling temperature and hydrogen-carbon weight ratio for the 98- to 99-percent aromatic fuels that was not apparent in figure 5. Again, inspection of the points at approximately constant values of volumetric average boiling temperature in the range from 170° to 182° F and from 360° to 380° F, carbon deposition increases with decrease in hydrogen-carbon weight ratio. The data in figure 7 thus indicate that carbon deposition may be a function of hydrogen-carbon weight ratio and volumetric average boiling temperature of the fuels.

An empirical method of correlating the carbon-deposition data of the 19 fuels obtained at engine operating condition 5 is shown in figure 8. The figure is divided into two quadrants; the left quadrant contains lines of constant hydrogen-carbon weight ratio and volumetric average boiling temperature; the right quadrant contains the weight of carbon deposited. The ordinate of the chart is obtained by moving up the volumetric average boiling temperature to the proper hydrogen-carbon weight-ratio curve. The weight of carbon obtained is then plotted against this value of the ordinate. The carbon-deposition data of the 19 fuels plotted in figure 8 can be approximated by one straight line. The two olefinic fuels, one aromatic fuel, and one fuel mixture deviate considerably from the faired curve and were not used for fairing the line. Although the amount of carbon obtained with the two olefinic fuels was small, there was soot-like carbon deposited on the walls of the tail-pipe section and the exhaust gases were smoky. No such deposit was obtained with the other hydrocarbon-type fuels.

The equation that represents the faired line in figure 8 and was derived by trial and error until correlation was obtained is

$$\log W_c = a + bK$$

where W_c is the weight of the carbon deposited and a and b are constants depending on the engine and the inlet-air and fuel conditions, and running time. The value of K, which is the ordinate of the chart, is determined by the hydrogen-carbon weight ratio and volumetric average boiling temperature of the fuel. The value of K depends on the fuel and is unaffected by engine operating conditions. The following equation determines K:

$$K = (t + 600)\ (0.7)\ \frac{H/C - 0.207}{H/C - 0.259}$$

where t is the volumetric average boiling temperature and H/C is the hydrogen-carbon weight ratio.

If the carbon deposition of two fuels at any one engine operating condition are determined, the constants a and b can be determined and the carbon deposition of other fuels can be estimated at the same engine operating condition.

Carbon-deposition data of the three fuels, aromatic solvent, benzene, and AN-F-32, investigated at the six engine operating conditions (fig. 3) are plotted in figure 9. This figure has the same relation of volumetric average boiling temperature to hydrogen-carbon weight ratio as figure 8. The value of K for any one fuel is the same for all engine operating conditions. If the assumptions used for the preceding equation are valid, the data should approximate a straight line, although the constants a and b will probably be different at each engine operating condition.

The data at engine operating conditions 1, 2, and 6 deviate somewhat from a faired straight line, although the same general trend is obtained at all engine operating conditions.

SUMMARY OF RESULTS

From carbon-deposition investigations of 19 fuels in a turbojet annular combustor with a diameter of $10\frac{3}{8}$ inches, the following results were obtained:

1. Carbon deposition decreased with increase in simulated altitude at constant simulated engine speed, and increased with increase in simulated engine speed from 50 to 100 percent of rated engine speed at a constant altitude of 20,000 feet.

2. In general, carbon deposition increased with increase in boiling temperature of the aromatic, paraffinic, and mixed fuels.

3. Carbon deposition increased with increase in aromatic content of fuels with approximately the same boiling temperature. Aromatic-type hydrocarbon fuels deposited more carbon than other types of fuel of the same boiling temperature.

4. An empirical correlation of the carbon deposition and the boiling temperature and hydrogen-carbon ratio of the fuel was obtained.

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TABLE I - PHYSICAL PROPERTIES AND CHEMICAL COMPOSITION

NACA fuel number	Fuel	Specific gravity 60°/60° F	Distillation A.S.T.M. Methods D 86-45 and D 850-47 (°F)					
			Percentage evaporated					Volumetric average boiling temperature
			10	30	50	70	90	
			Paraffinic hydro					
46-111	Commercial isoheptanes	0.725	176	180	180	184	192	182
46-254	Paraffinic solvent	.775	336	340	344	350	368	348
			Olefinic hydro					
46-152	Diisobutylene	0.724	209	210	210	211	213	211
47-50	n-Hexadecene-1	.785	522	522	522	524	526	523
			Aromatic hydro					
46-219	Benzene	0.882	172	172	172	172	173	172
47-152	50-percent benzene and 50-percent aromatic solvent[h]	.877	195	212	257	325	333	264
46-338	Ethylbenzene	.871	268	270	270	270	272	270
46-71	Xylenes	.866	276	278	278	278	281	278
46-133	Aromatic solvent	.874	322	324	324	326	328	325
47-353	30-percent α- and β-monomethylnaphthalene and 70-percent aromatic solvent[h]	.914	330	340	350	374	450	369
47-173	Triisopropylbenzene	.861	440	442	444	445	448	444
46-216	α- and β-monomethylnaphthalene	1.016	458	458	460	460	460	459
			Mixed hydro					
47-150	50-percent commercial isoheptanes and 50-percent benzene[h]	0.792	168	169	170	172	177	171
44-821	AN-F-28R	.728	144	181	217	243	290	215
47-153	50-percent commercial isoheptanes and 50-percent AN-F-32[h]	.766	191	211	257	371	427	291
47-151	50-percent AN-F-32 and 50-percent aromatic solvent[h]	.840	330	340	351	368	412	360
47-186	AN-F-32	.830	345	361	371	387	415	376
47-114	Michigan crude	.814	490	502	512	526	554	517
47-115	Diesel oil	.836	462	490	516	546	604	524

[a]Reference 6.
[b]Reference 7.
[c]Reference 8.
[d]Reference 9.
[e]Estimated.
[f]Calculated.
[g]Reference 10.
[h]Percent by weight.

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OF FUELS USED IN CARBON-DEPOSITION INVESTIGATION

Hydrocarbon analysis				Hydrogen-carbon weight ratio	Net heat of combustion (Btu/lb)
Aromatics (percent by volume)[a]	Naphthene ring (percent by weight in saturates)[b]	Olefins (percent by weight)[c]	Dicyclic aromatics (percent by volume)[d]		
carbon fuels					
-----------	28	-----------	-----------	0.177	18,900
2	27	-----------	-----------	.179	18,800
carbon fuels					
-----------	-----------	98	-----------	0.170	18,820
-----------	-----------	98	-----------	.166	18,865
carbon fuels					
[e]98	-----------	-----------	-----------	[f]0.084	[g]17,260
[e]98	-----------	-----------	-----------	[f].099	[f]17,430
[e]98	-----------	-----------	-----------	[f].105	[g]17,600
[e]98	-----------	-----------	-----------	.109	17,600
98	-----------	-----------	-----------	.115	17,600
[f]99	-----------	-----------	[f]27	[f].104	[f]17,360
[e]98	-----------	-----------	-----------	.132	18,000
99	-----------	-----------	99	.079	16,800
carbon fuels					
[f]44	[f]28	-----------	-----------	[f]0.129	[f]18,080
16	3	-----------	-----------	.174	18,600
[f]6	[f]37	-----------	-----------	.169	18,700
[f]54	[f]48	-----------	-----------	.139	[f]18,075
13	48	-----------	-----------	.162	18,550
16	6	-----------	2.5	.165	18,600
23	27	-----------	3.0	.159	18,550

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TABLE II - CARBON DEPOSITION AND COMBUSTION EFFICIENCY OF VARIOUS FUELS OBTAINED IN $10\frac{3}{8}$-INCH-DIAMETER ANNULAR COMBUSTOR

[Engine operating condition 5: inlet-air total pressure, 40 in. Hg absolute; inlet-air total temperature, 100° F; fuel flow, 157.5 lb/hr; over-all fuel-air ratio, 0.0175; running time, 2 hr.]

Fuel	Carbon deposition (grams)	Average carbon deposition (grams)	Turbine-inlet total temperature (°F)	Combustion efficiency (percent)
Paraffinic hydrocarbon fuels				
Commercial isoheptanes	1.0	---------	1300	97
Paraffinic solvent	2.0	1.8	1300	97
	1.6	---------	---------	---------
Olefinic hydrocarbon fuels				
Diisobutylene	4.1	---------	1250	93
n-Hexadecene-1	2.3	---------	1265	93
Aromatic hydrocarbon fuels				
Benzene	27.8	33.5	1210	95
	42.6	---------	---------	---------
	28.8	---------	---------	---------
	34.6	---------	---------	---------
50-percent benzene and 50-percent aromatic solvent[a]	56.1	---------	1210	96
Ethylbenzene	44.8	---------	1215	95
Xylenes	52.5	---------	1180	92
Aromatic solvent	51.5	51.5	1225	94
	51.4	---------	---------	---------
30-percent α- and β- monomethylnaphthalene, and 70-percent aromatic solvent[a]	140.5	---------	1120	87
Triisopropylbenzene	88.3	---------	1230	94
α- and β-monomethylnaphthalene	138.8	133.9	1090	92
	129.0	---------	---------	---------
Mixed hydrocarbon fuels				
50-percent commercial isoheptanes and 50-percent benzene[a]	13.7	---------	1295	98
AN-F-28R	1.4	---------	1280	95
50-percent commercial isoheptanes and 50-percent AN-F-32[a]	3.3	---------	1335	98
50-percent AN-F-32 and 50-percent aromatic solvent[a]	26.5	---------	1235	93
AN-F-32	6.8	8.0	1280	96
	10.9	---------	---------	---------
	6.4	---------	---------	---------
Michigan crude	6.8	6.4	1285	97
	6.0	---------	---------	---------
Diesel oil	31.7	---------	1255	95

[a]Percent by weight.

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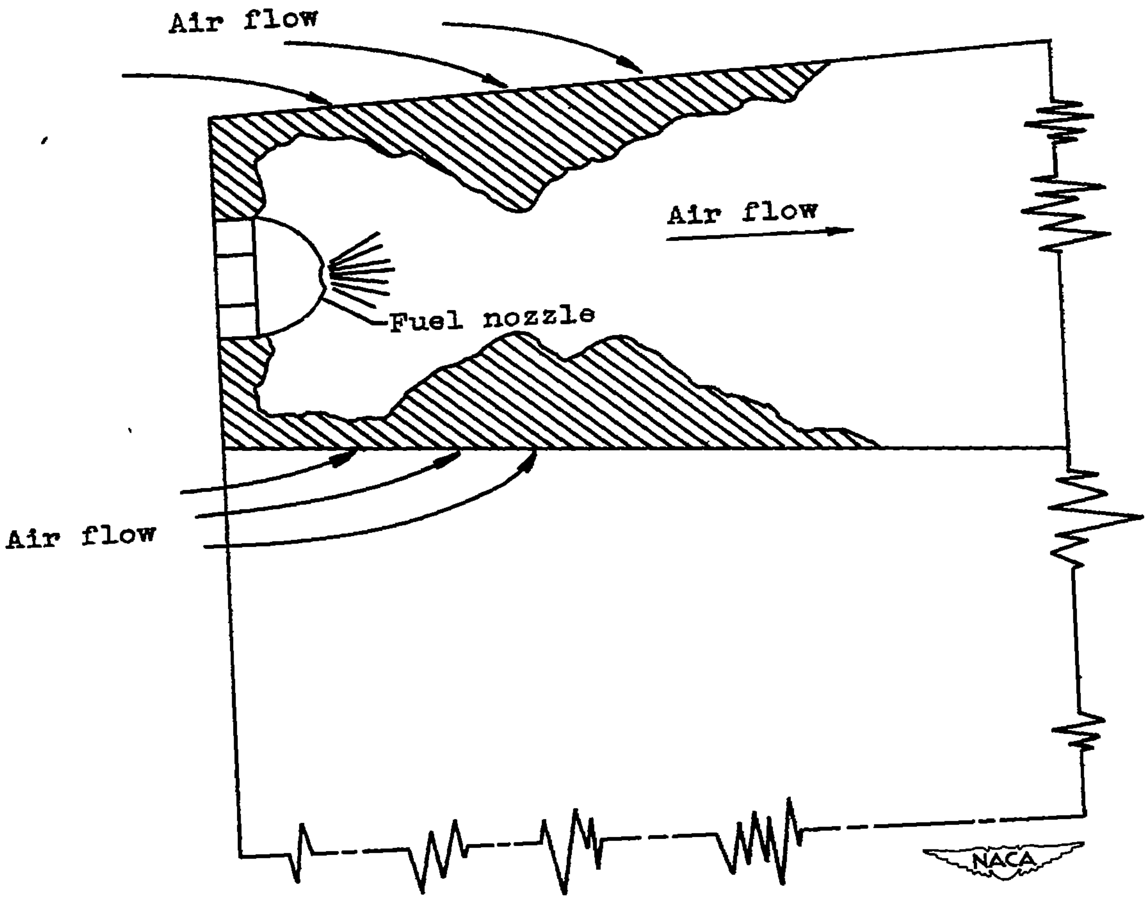

Figure 1. - Diagrammatic sketch of cross section of carbon deposition in annular-type combustor.

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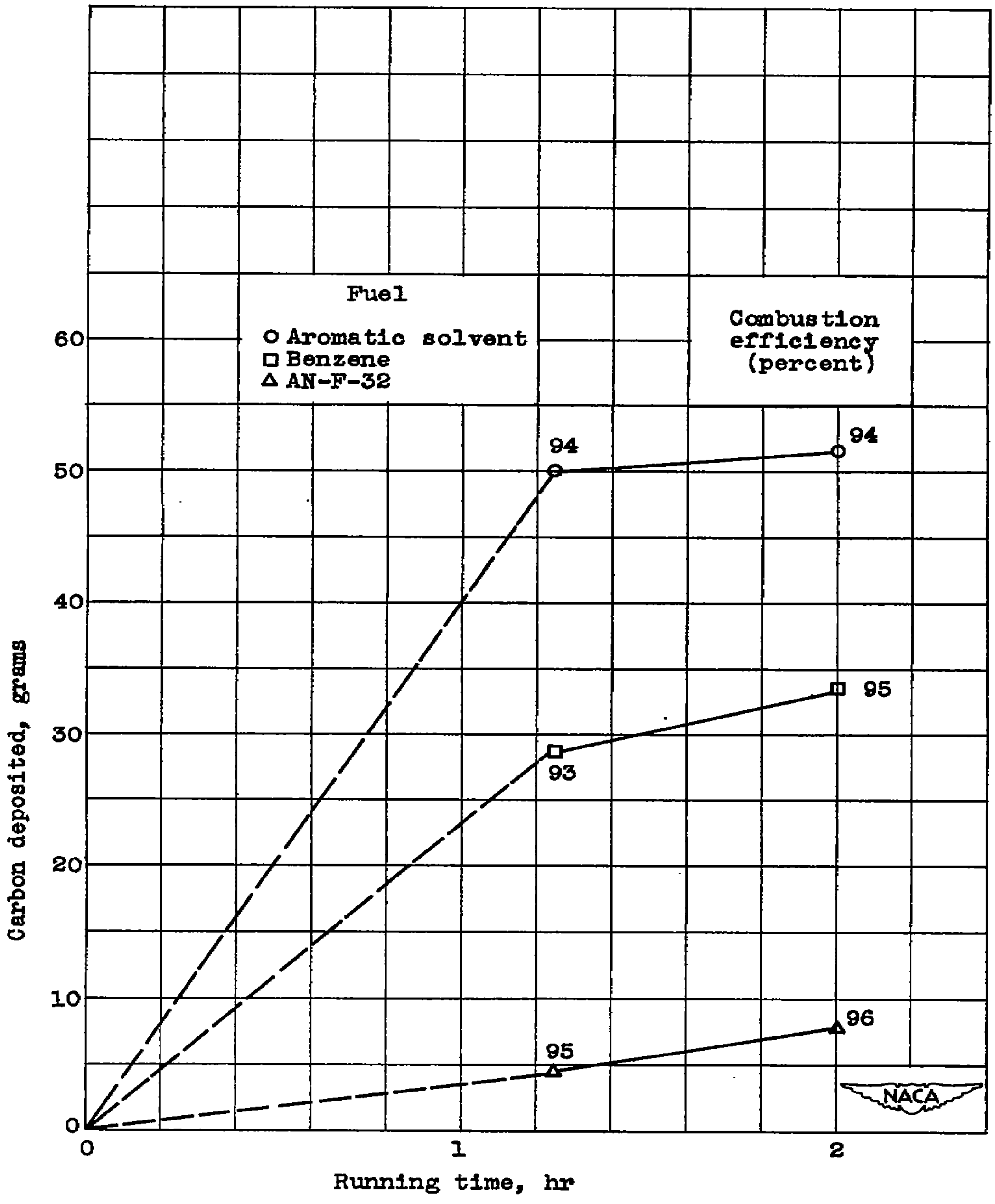

Figure 2. - Carbon deposition of three fuels as determined by running time. Annular-combustor diameter, $10\frac{3}{8}$-inches; inlet-air total pressure, 40 inches mercury absolute; inlet-air total temperature, 100° F; fuel flow, 157.5 pounds per hour; over-all fuel-air ratio, 0.0175.

Simulated engine operating condition	1	2	3	4	5	6
Simulated altitude, ft x 10^{-3}	40	20	30	0	0	20
Simulated engine speed, percentage rated	100	50	100	50	50	100
Inlet-air total pressure, in. Hg absolute	19.0	18.9	30.8	40.0	40.0	44.0
Inlet-air total temperature, °F	132	43	153	100	100	196
Fuel flow, lb/hr	155.5	116.5	172.0	157.5	157.5	223.0
Over-all fuel-air ratio	0.0282	0.0224	0.0202	0.0175	0.0175	0.0181
Running time, hr	$1\frac{1}{4}$	$1\frac{1}{4}$	$1\frac{1}{4}$	$1\frac{1}{4}$	2	$1\frac{1}{4}$

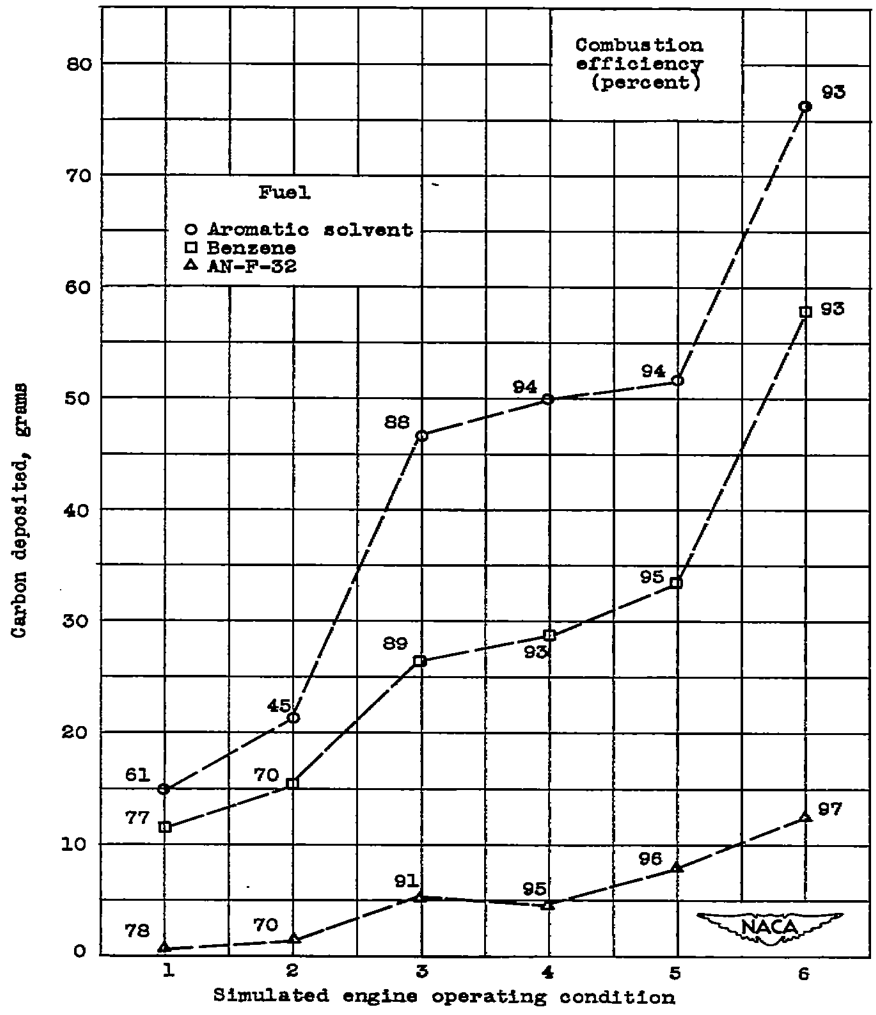

Figure 3. - Carbon deposition of three fuels as determined by simulated engine conditions. Annular-combustor diameter, $10\frac{3}{8}$ inches.

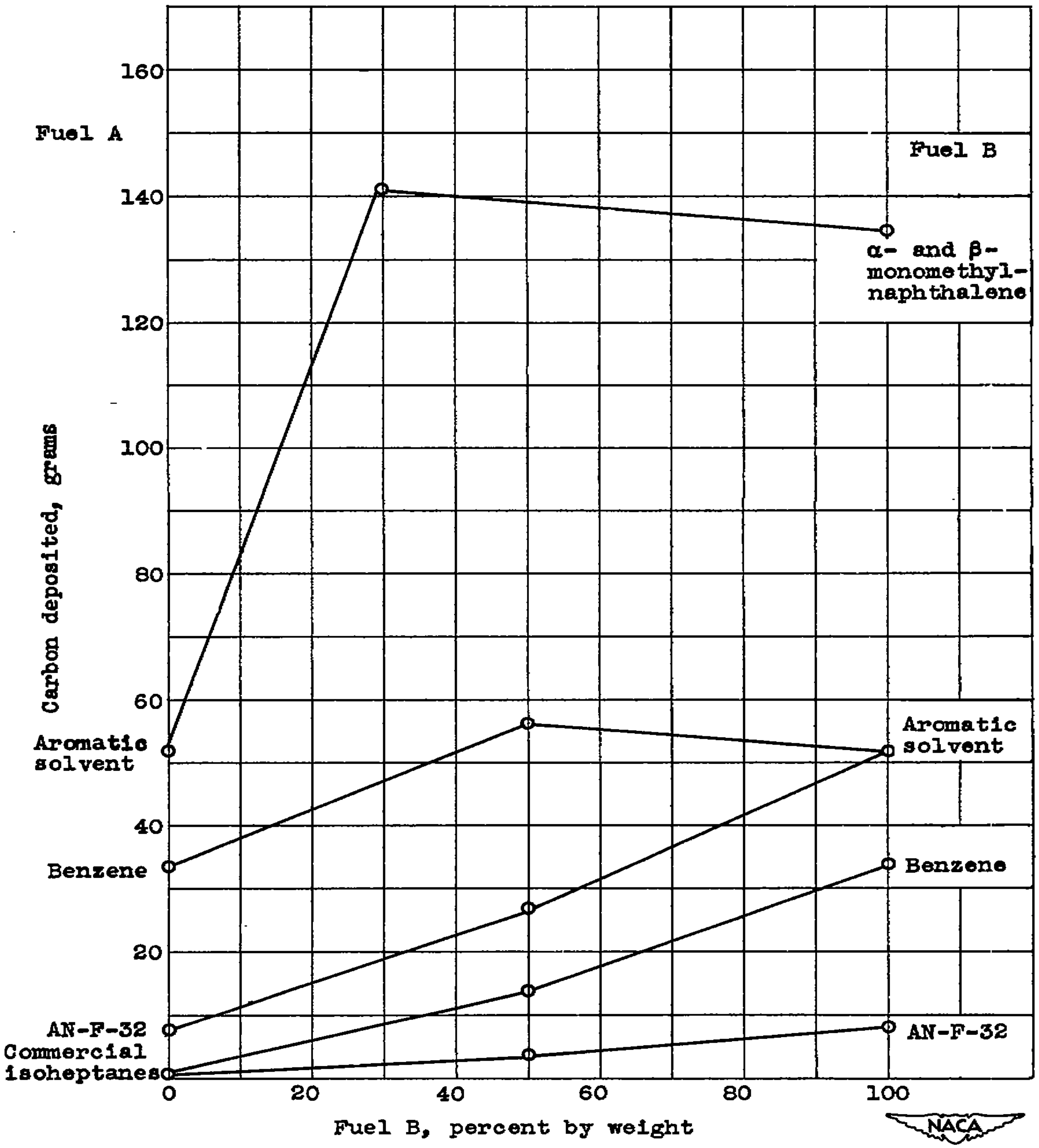

Figure 4. - Carbon deposition as determined by fuel blends. Annular-combustor diameter, $10\frac{3}{8}$-inches; inlet-air total pressure, 40 inches mercury absolute; inlet-air total temperature, 100° F; fuel flow, 157.5 pounds per hour; over-all fuel-air ratio, 0.0175; running time, 2 hours.

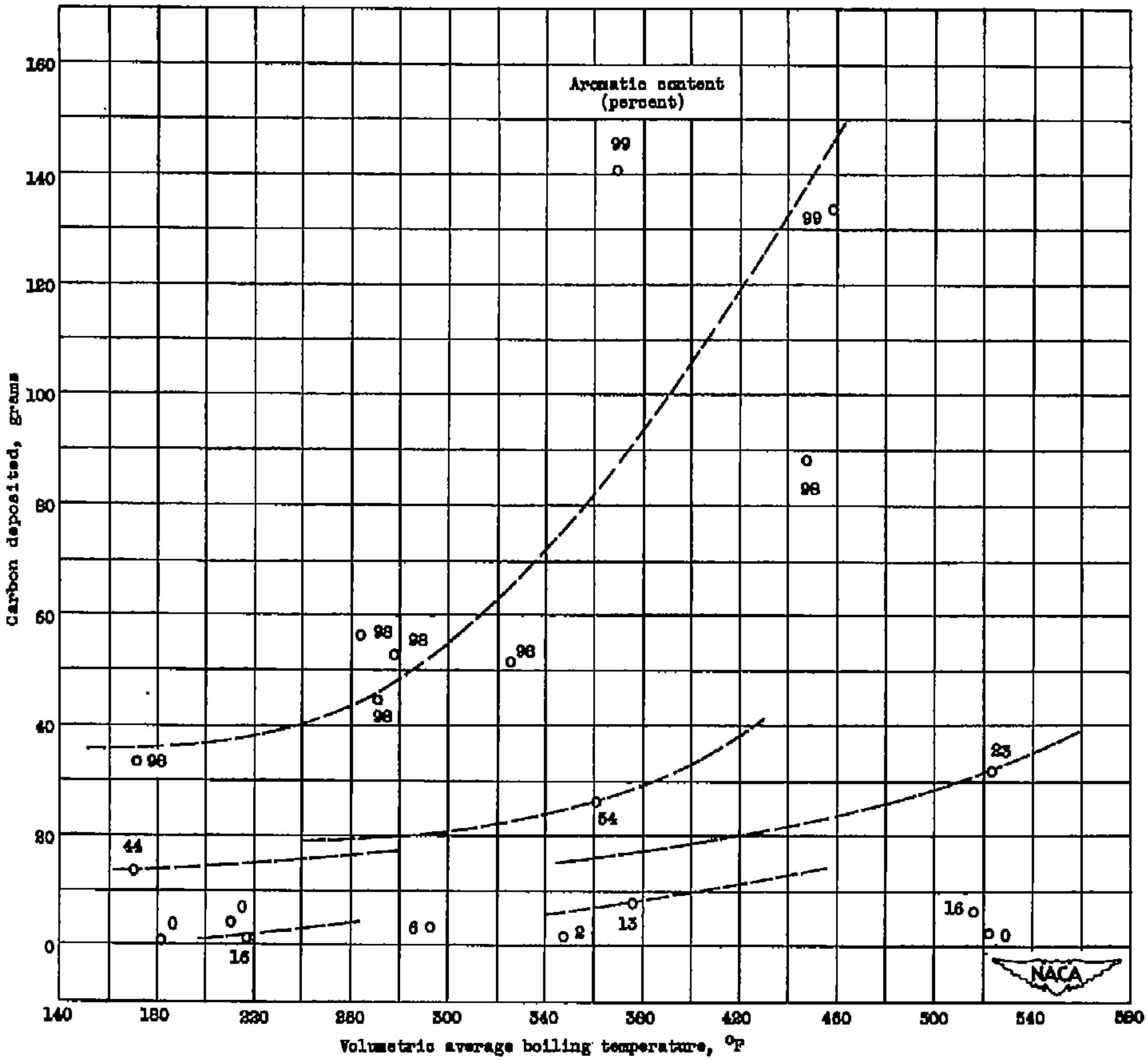

Figure 5. - Carbon deposition of 19 fuels as determined by volumetric average boiling temperature and aromatic content. Annular-combustor diameter, $10\frac{3}{8}$ inches; inlet-air total pressure, 40 inches mercury absolute; inlet-air total temperature, 100° F; fuel flow, 157.5 pounds per hour; over-all fuel-air ratio, 0.0175; running time, 2 hours.

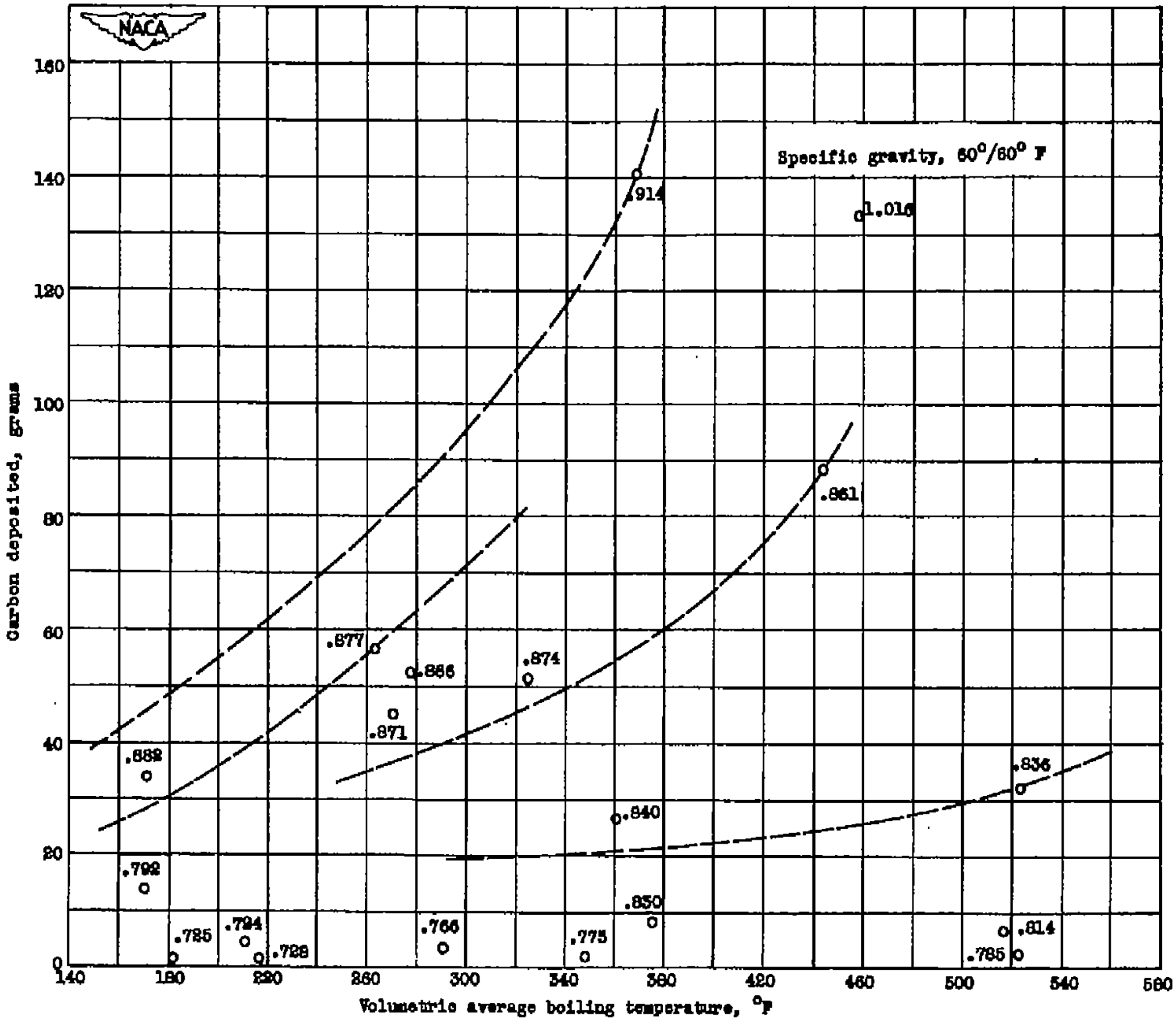

Figure 8. - Carbon deposition of 19 fuels as determined by volumetric average boiling temperature and specific gravity. Annular-combustor diameter, $10\frac{3}{8}$ inches; inlet-air total pressure, 40 inches mercury absolute; inlet-air total temperature, 100° F; fuel flow, 157.5 pounds per hour; over-all fuel-air ratio, 0.0175; running time, 2 hours.

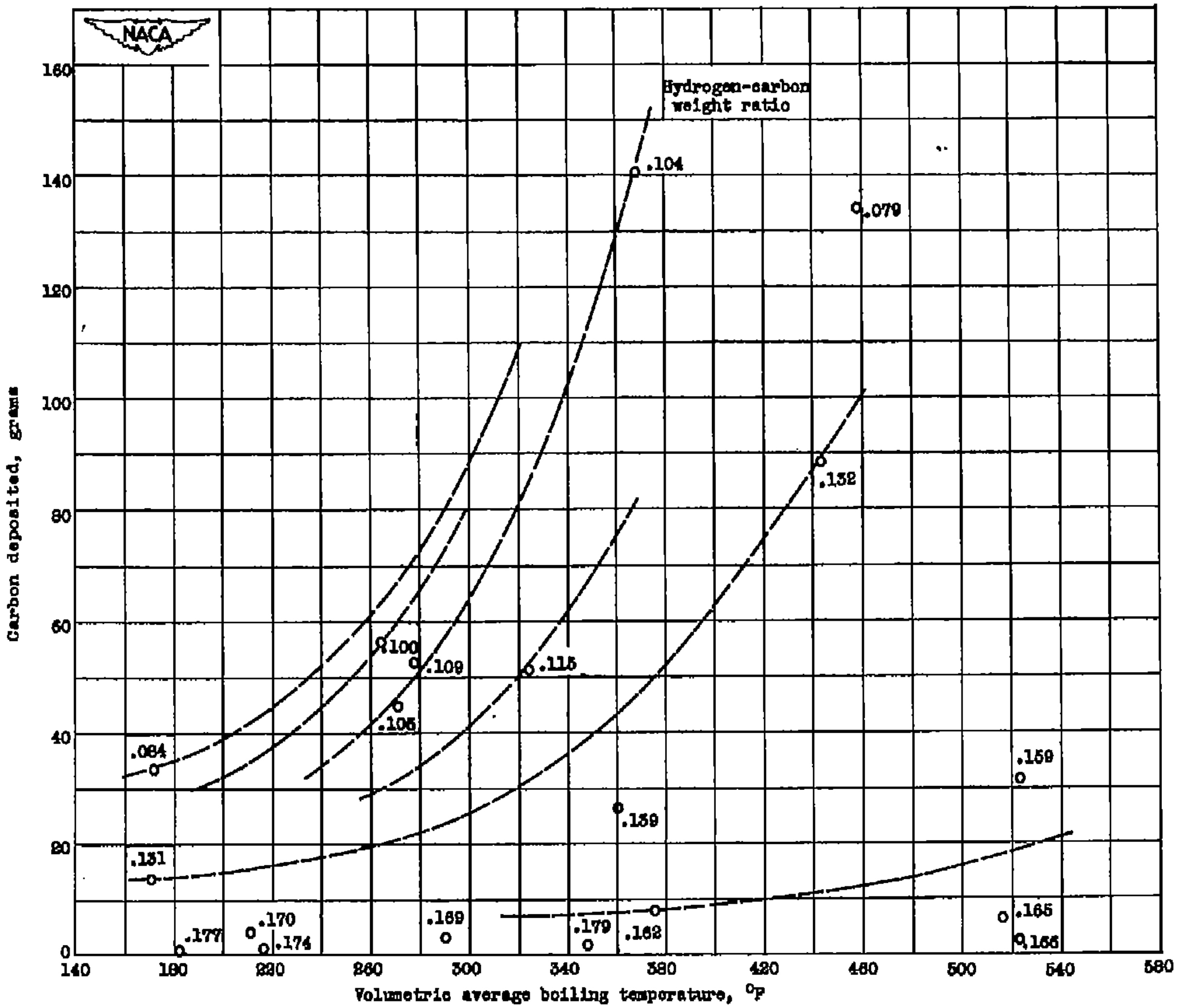

Figure 7. - Carbon deposition of 19 fuels as determined by volumetric average boiling temperature and hydrogen-carbon weight ratio. Annular-combustor diameter, $10\frac{3}{8}$ inches; inlet-air total pressure, 40 inches mercury absolute; inlet-air total temperature, 100° F; fuel flow, 157.5 pounds per hour; over-all fuel-air ratio, 0.0175; running time, 8 hours.

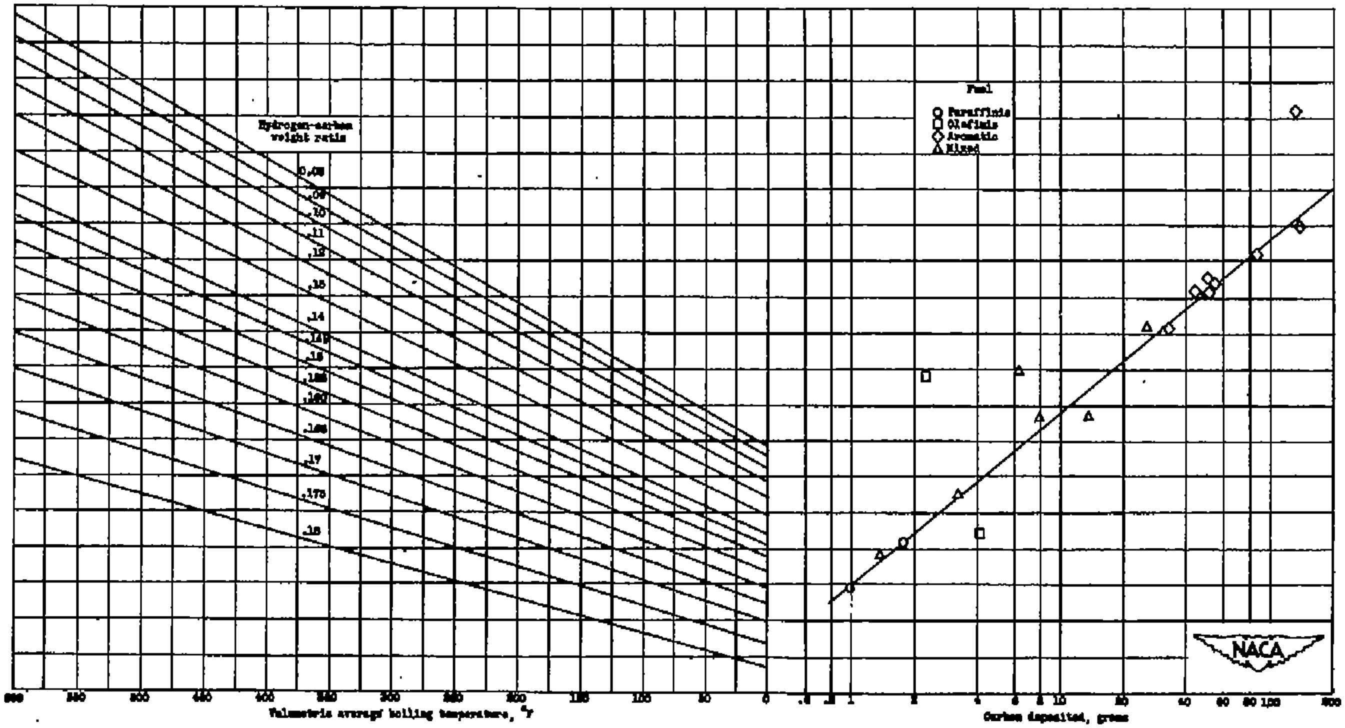

Figure 8. - Carbon deposition of 19 fuels as determined by volumetric average boiling temperature and hydrogen-carbon weight ratio. Annular-combustor diameter, $10\frac{3}{8}$ inches; inlet-air total pressure, 40 inches mercury absolute; inlet-air total temperature, 100° F; fuel flow, 157.5 pounds per hour; over-all fuel-air ratio, 0.0175; running time, 2 hours.

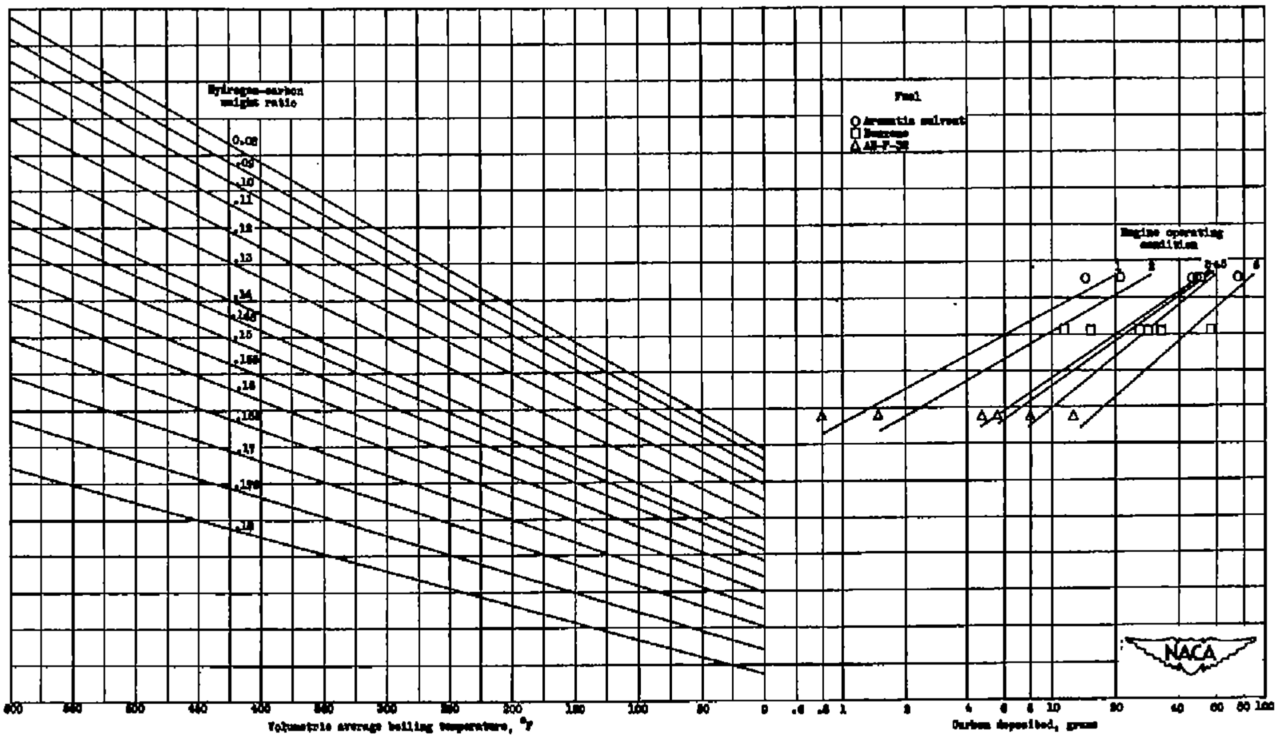

Figure 9. - Carbon deposition of three fuels as determined at simulated engine conditions listed in figure 3. Annular-combustor diameter, $10\frac{3}{8}$ inches.